DISCRIMINATION CAPABILITY FOR MINING EVENTS IN THE ALTAI-SAYAN REGION OF RUSSIA AND THE WESTERN UNITED STATES

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ABSTRACT

As more seismic and infrasound stations and arrays are deployed for nuclear explosion monitoring, catalogs of seismic events contain not only earthquakes, but many types of anthropogenic sources. Mining events are commonly recorded at regional distances by these stations, with the possibility of misidentification, (e.g., a legitimate mining explosion mistaken as nuclear). Additionally, a nuclear explosion could potentially be embedded in a mining explosion and be missed. Different discriminants have been utilized to separate mining events from natural seismicity with varying degrees of success. In this paper we present results of ongoing efforts to test several discriminants (amplitude ratios, time varying spectral analysis, time-of-day analysis, and infrasound) for two active mining regions: the Powder River Basin (PRB) in the western United States and the Altai-Sayan (AS) in Russia. The first phase of work on this contract has focused on using seismic and infrasound data in the PRB as a test bed for developing and assessing different mining explosion discriminants. This work is outlined in detail by Arrowsmith et al. (2006a, 2007). The results obtained indicate that phase amplitude discriminants, which have been found to be successful in separating earthquakes from nuclear explosions, do not separate earthquakes and mining explosions in this region, probably due to a combination of source and path effects. However, a time-varying spectral discriminant developed as part of this project was very successful at identifying the largest types of mining explosions (cast blasts). We also identified infrasound signals from large mining explosions in this region, suggesting good potential for the use of infrasound as an additional discriminant in this region when winds are favorable.

The AS region is the largest Russian exporter of coal, with over 26 surface coal mines in operation and events ranging from 60 to 700 tons in size. In cooperation with scientists at the Siberian Geophysical Survey, we compiled a catalog of 263 earthquakes and 843 probable mining events. Despite efforts to gather ground truth information on the mining events in the catalog, little is known about the blasting practices utilized for any of the assumed mining events in the database. Therefore, the criteria used in identifying events as either natural or manmade remain poorly defined. Based on the results of our analysis in the PRB, we applied similar techniques to the AS database to compare discrimination capability for purportedly comparable events. We selected two stations for our analysis: the International Monitoring System (IMS) station ZAL and Incorporated Research Institutions for Seismology (IRIS) station KURK. We selected 69 earthquakes and 260 mining events at ZAL and 41 earthquakes and 68 mining events at KURK for detailed analysis based on signal quality and first arrival picks. We performed a time-of-day analysis with respect to location by investigating daytime events versus nighttime events as a function of geographic location based on work by McCarthy et al. (2007). Daytime events clearly correlate with known mining locations, and earthquakes show a mix of both daytime and nighttime activity within the whole AS. Using the subset of data, we computed various amplitude ratios. There were no amplitude ratio discriminants at either station that clearly separated mining events from earthquakes, regardless of whether a distance correction (such as magnitude and distance amplitude corrections [MDAC]) was applied. Finally, we utilized time-varying spectral analysis. We applied multiple combinations of training parameters, but no combination of parameters successfully separated the two event classes in this region. Although these results are disappointing, they do not necessarily indicate that these two discriminants are ineffective for this region because the ground-truth information is insufficient to fully assess this capability. Based on experience in the PRB we review these findings and outline types of ground-truth information that would be required to fully assess discriminant capability for future studies of this type.

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OBJECTIVES

This paper delineates research progress toward the following two objectives:

I. Continued Development of Discriminants and Application to the Testing Dataset in Wyoming

The first objective for this phase of our project was to continue the development of mining explosion discriminants, in particular the infrasound and amplitude discriminants, in conjunction with testing using the subset of data in Wyoming (see Arrowsmith et al., 2006, for more details on the dataset).

II. Application of Discriminants to a New Region: Altai-Sayan in Russia

The second objective for this phase of our project was to apply the seismic discriminants (time-frequency and amplitude ratios) to data from a different region with a different tectonic structure and different blasting practices. The purpose of this is to assess the portability of these discriminants to different regions.

RESEARCH ACCOMPLISHED

I. Powder River Basin in Wyoming, USA

In this paper we build on our previous paper (Arrowsmith et al., 2006c) with regard to the continued development of discriminants. There we described a time-frequency discriminant, which is applicable to either single stations or arrays, and applied it to the subset of data from Wyoming (Figure 1). The results showed that the time-frequency discriminant was very effective at distinguishing large open-pit mining explosions ("cast blasts") from earthquakes, but less successful at distinguishing smaller explosions. The method was found to successfully identify 97% of events in a blind test (comprising earthquakes and cast blasts). We also tested traditionally well-performing amplitude discriminants, such as high-frequency Pg/Lg, on regional phase amplitudes from both mining events and earthquakes near the PDAR seismic array. Initial results indicated that this is a poorly performing discriminant, evidenced by variability in Pg and Lg amplitudes for similar event types at high frequencies.

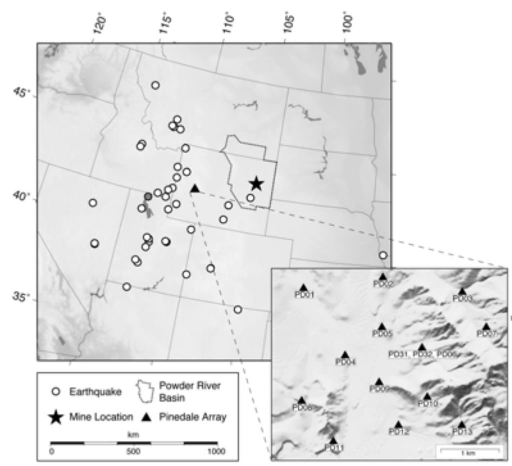

Figure 1. The PDAR seismic array (triangles) located in western Wyoming, USA. Circles represent the subset of earthquakes used in the 2006 study; the star represents locations of mining events that were analyzed.

Amplitude ratio discriminant

We have extended our investigation of the amplitude ratio discriminant in this region by considering additional earthquakes that lie along the path between the mine location and the PDAR array and by integrating a set of single-fired explosions detonated at the same mine in 1995 and 1997 (Stump et al., 2003), to ascertain whether or not path effects are affecting discrimination capability or whether the source types at this mine simply do not discriminate against background population. Figure 2 shows Pg/Lg (6–8 Hz) discriminant values for earthquakes and for different types of mining events (see Arrowsmith et al., 2006c, for a description of these types of events).

None of the event types discriminate from the earthquake population, which is particularly surprising for the single-fired events, which would be expected to be more explosion-like in terms of discrimination capability.

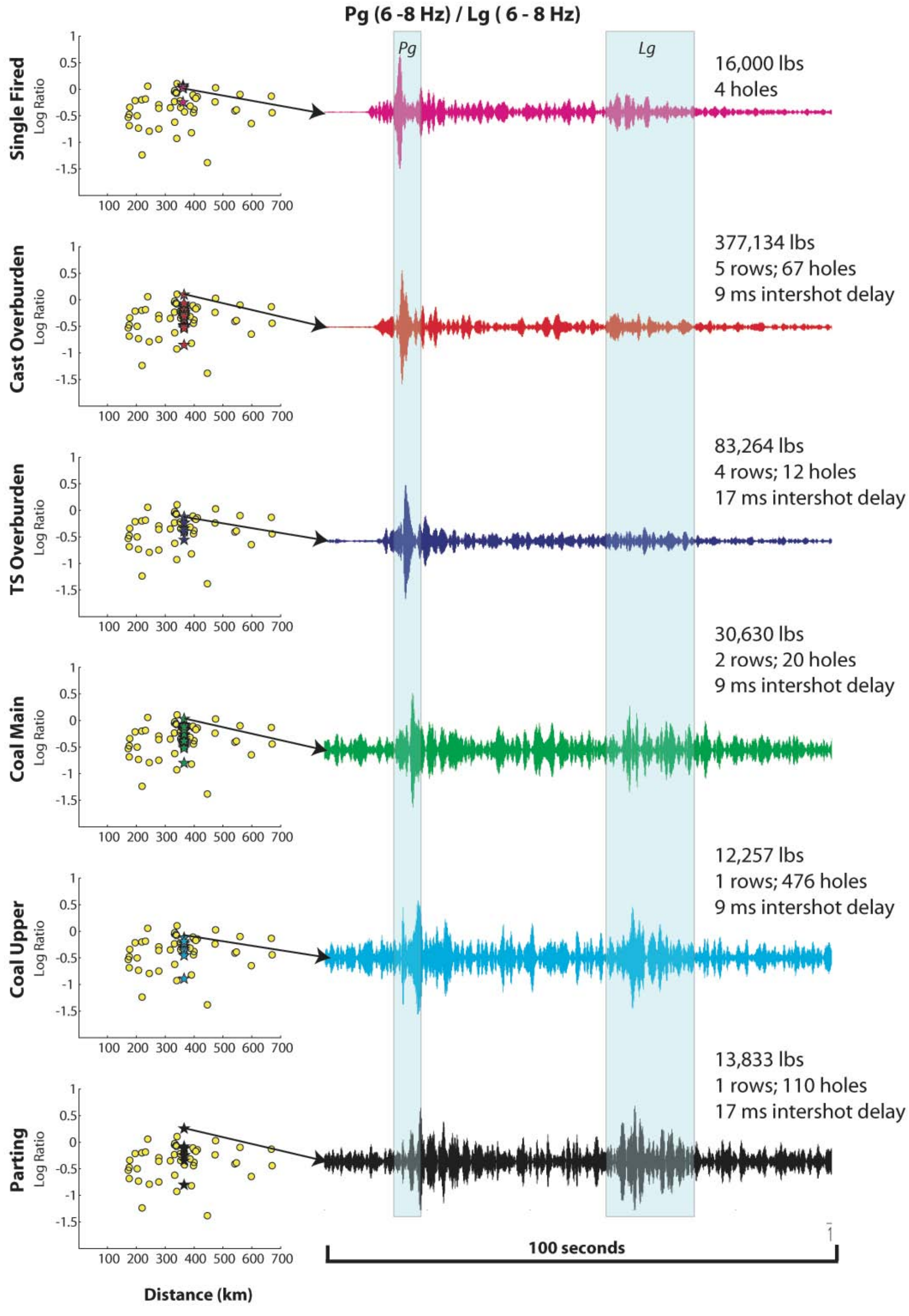

Figure 2. MDAC-corrected discriminant values at PDAR station PD31 (broadband vertical component) for six different types of mining events, as a function of distance. Waveforms for selected events are shown at the right, bandpass filtered in the 6–8 Hz band, with the Pg and Lg phase highlighted. Detonation information about the event is given as well.

In addition to investigating different mining event types, we have also looked at the uncorrected discriminant values for the earthquake population to determine if any regional trends emerged. Figure 3 shows earthquake Pg/Lg (6–8 Hz) Hz values as a function of location. Hotter colors indicate more explosion-like events, while cool colors show earthquake-like events. Those events on the path from the mine location (red square) and PDAR (yellow square) generally discriminate better from the explosions that traverse the same path—a promising conclusion. We are continuing to evaluate this problem by looking at additional regional stations that surround the mine at a variety of azimuths.

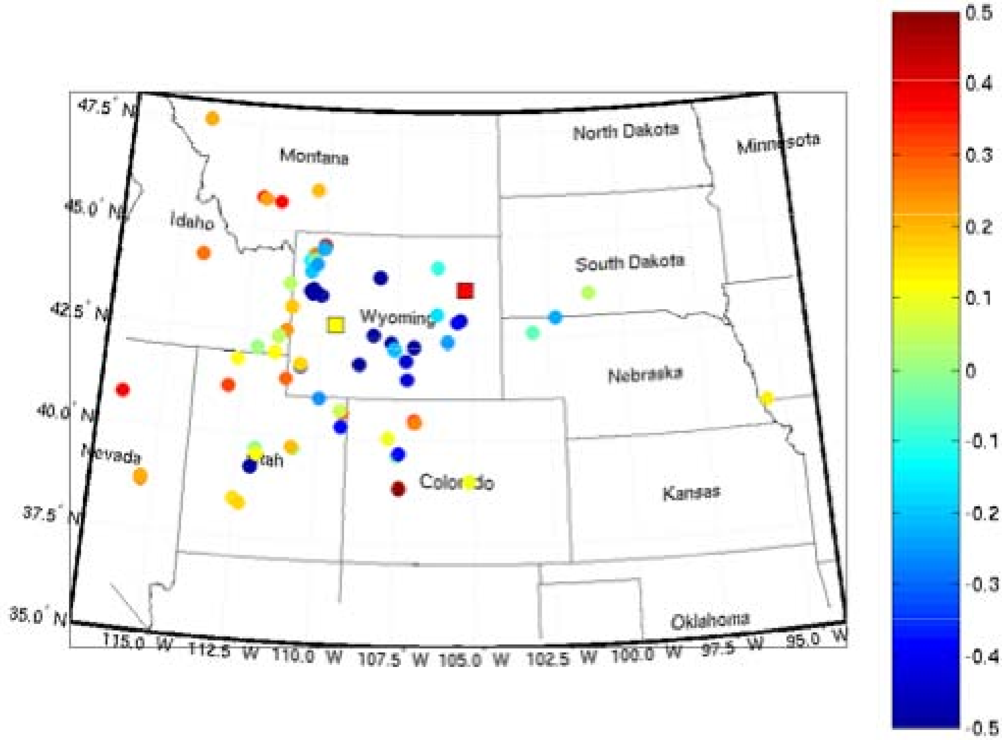

Figure 3. Uncorrected earthquake discriminant values (Pg/Lg (6–8 Hz)) at PDAR (yellow square) as a function of location. The mine location is indicated by the red square.

Infrasound discriminant

We have assessed the use of infrasound as a discriminant for mining explosions by studying the ability to detect infrasound signals from large ground-truth cast blasts at the PDIAR infrasonic array in Wyoming (Figure 4). We have also assessed the factors that influence the ability to detect mining explosions through a detailed noise analysis and propagation modeling. Unfortunately, we have found that PDIAR is a very noisy array (Figure 4) compared with typical levels of ambient infrasonic noise (Bowman et al., 2005). This implies that the potential for infrasound as a mining explosion discriminant must be reassessed for typical noise-level sites. However, we have developed a robust scheme for associating infrasound signals with known events (either through acquired ground-truth or seismically derived event bulletins). We have also observed four high-quality signals at PDIAR from mining explosions (out of a total of 32 events). The signals (Figure 5) are typically observed during summer months, when the wind directions are favorable and ambient noise levels are relatively low. The ray-tracing modeling backs up these observations by demonstrating that variations in atmospheric properties play an important role in whether or not we observe detections. However, although ambient noise levels and propagation modeling can explain most of the observations, they do not completely satisfy the observations. A further variable that we do not have any constraint on is the source size, and we speculate that this may explain the outlying observations, although un-modeled variations in atmospheric properties may also play a role.

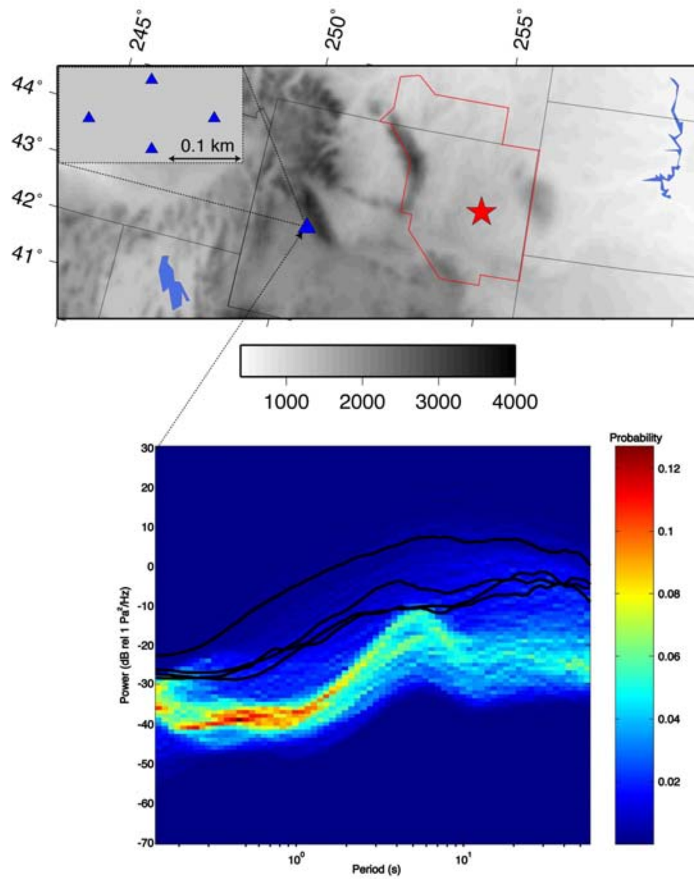

Figure 4. The PDIAR infrasound array. Top panel: Location of the PDIAR array (blue triangle) in relation to the location of the mine (red star) in the Powder River Basin (shown by the red line). The distance from the mine to the array is approximately 368 km. Bottom panel: Probability density function of the ambient noise power spectral density at PDIAR. The black lines show spectra of signals that were detected in the 1–5 Hz band.

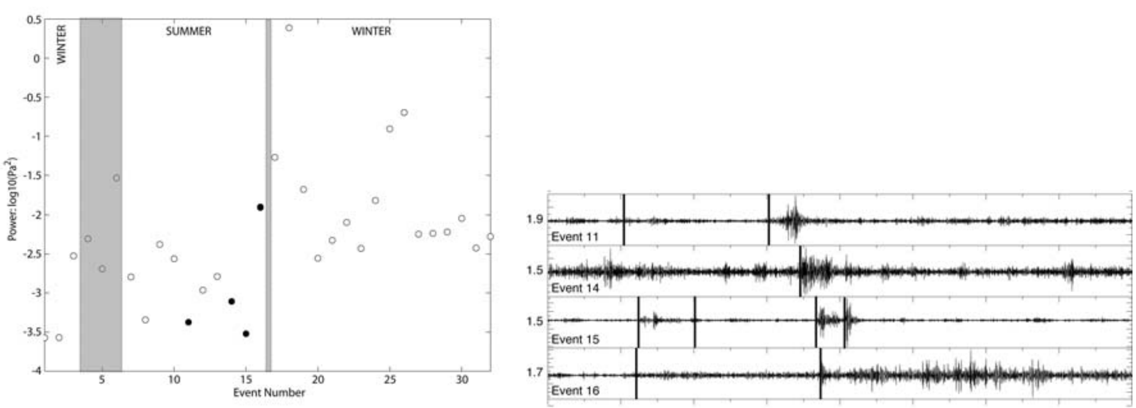

Figure 5. Infrasonic detections from cast blasts in Wyoming. Left panel: Detected shots (solid circles) and undetected shots (open circles) as a function of event number, which increases in relation to time. Gray regions indicate transitional months for stratospheric winds. Right panel: Beam-formed waveforms for the four high-quality detections (individual phase arrivals are denoted by solid vertical lines). The pre-event noise power is plotted on the vertical axis in both panels.

II. Altai-Sayan in Siberia, Russia

The AS (Figure 6) is an active mining region with numerous types of mines and quarries, including iron ore, zinc, copper, lead, molybdenum, bauxite, gold, and silver; this region is also Russia's top producer of coal. Approximately 40% of active surface coal-mines in Russia are in the AS. The region also has prevalence of natural seismicity due to the Asia-India collision zone to the south and the Baikal rift zone to the east. These factors make the region an ideal test bed for discrimination techniques designed to separate signals from earthquakes and mining explosions, including time-of-day analysis, amplitude ratios, and time-frequency analysis.

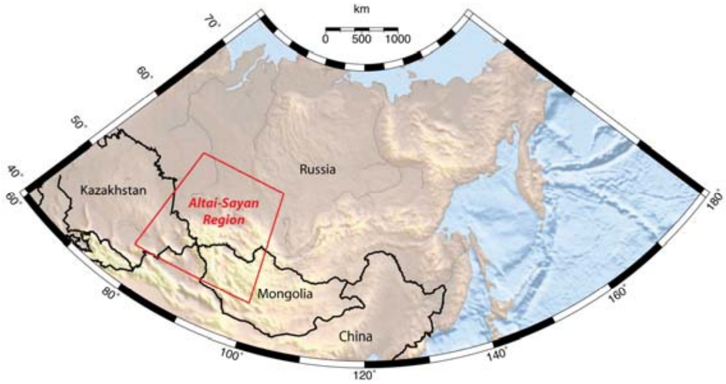

Figure 6. The Altai-Sayan region (red) is located in western Siberia and encompasses portions of Kazakhstan, Mongolia, and China. Subsequent figures of the Altai-Sayan region mirror the outlined area in this figure.

In order to assemble a database containing natural and mining-related events, we collaborated with scientists from the Altai-Sayans Seismological Expedition (ASSE), who provided us event lists (location, origin time, and m_b converted from Russian K class) of 263 probable earthquakes and 843 probable mining explosions. We were not provided the criteria for how ASSE seismologists classified event types. Literature reviews (e.g., Rautian and Leith, 2002) suggest that time-of-day criteria are most commonly used, but ASSE scientist Albina Filena (1999) notes that other methods are sometimes used, including surface wave analysis and comparison of the ratios of transverse to longitudinal waves.

The ASSE maintains a dense network of stations in the AS region, but due to various issues, we were unable to gain access to this data, and instead requested data from five seismic stations (ZAL, KURK, MAKZ, TLY, and BRVK) using the event catalogs provided to us by the ASSE. From these five stations, we gathered approximately 24,000 waveforms. For the study presented here, we discuss results from IMS station ZAL and IRIS station KURK. Station ZAL is a short-period three-component station that has known instrument response problems (see Acknowledgements section), so measurements relying on instrument-corrected data (such as amplitudes) should be given scrutiny. KURK is a three-component broadband station that has undergone various instrument response changes in the past ten years. A noise study (Arrowsmith, 2006b) at this station shows that noise amplitudes vary as a function of time, indicating there may be problems with the available instrument responses at this station as well.

Of the 263 earthquakes and 843 mining explosions for which we requested data from ZAL and KURK, we selected 329 events at ZAL (69 earthquakes and 260 mining events) and 109 events at KURK (41 earthquakes and 68 mining events) for further analysis. These waveforms were selected based on signal quality (no glitches or data dropouts, single event per waveform) as well as on the ability to pick a first arrival (i.e. signal-to-noise quality). Figure 7 shows distance distributions of the events, as well as event locations with respect to station location for this subset of events. All events are at regional or near-regional distances. The signal-to-noise ratio (SNR) of the data subset indicates that at ZAL, the SNR is greatest between frequencies of 1 and 8 Hz. At KURK, where event-station distances are greater, SNR quality is much lower. For the earthquake population, the best SNR is found between 1 and 4 Hz for all phases. For the mining events, the optimal frequency bands for analysis are between 1 and 8 Hz for all phases.

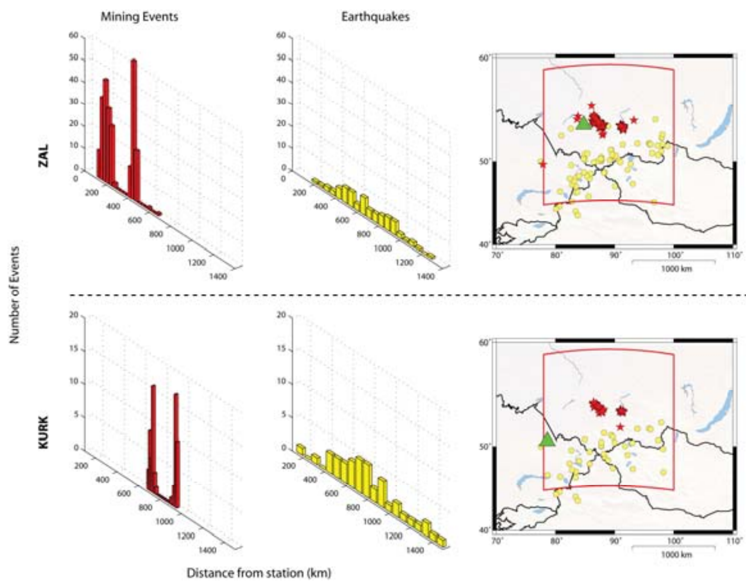

Figure 7. Distance and location distributions for selected events at ZAL (top panels) and KURK (bottom panels). Red events are probable mining events and yellow events are probable earthquakes. Station locations (right column) are noted as green triangles.

Time-of-day discriminant

In a region where we have limited ground truth, an important discriminant is the time-of-day information. While time-of-day information is not based on waveform metrics, it is a valuable criterion for providing information on the broad types of events that occur in specific regions. Analysis of time-of-day as a function of event location effectively outlines regions of mining activity (where the dominant percentage of daytime events occur in regions of known mine locations). Figure 8 shows the distribution of events with respect to month and hour for both mining explosions and earthquakes at ZAL and KURK. Mining events clearly occur during working hours, while the earthquakes exhibit no clear time-of-day dependence, providing confidence in the event bulletins supplied to us by the ASSE. These results also illustrate that time-of-day is not the sole criterion used by the ASSE in constructing the event bulletins, since the earthquakes also occur during working hours. A study such as that of MacCarthy et al. (2007), which utilizes time-of-day information in conjunction with satellite imagery and waveform cross correlation, could further provide constraints on anomalously timed events (e.g., several probable mining events in the total database, as classified by the ASSE, which occur at non-traditional working hours).

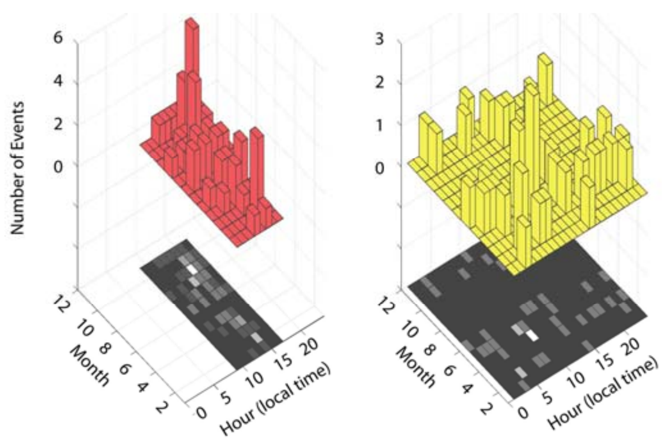

Figure 8. Time-of-day distribution with respect to month and hour of day for the ZAL/KURK data subset for both probable mining events (left) and earthquakes (right). Surface reflections of the histograms show trends, where lighter colors indicate larger numbers of events.

Amplitude ratio discriminant

In order to process the data for amplitude measurement, we measured the identified regional phases (Pn, Pg, Sn, and Lg) on the vertical components of both ZAL (short-period) and KURK (broadband) as well as on the radial and tangential components. We used a regional 1D velocity model of the AS as guidance for predicted phase arrival times. Picks were made on events where event signals could confidently be delineated above background noise levels after high passing the data at 1 Hz. The picked waveforms were instrument corrected to displacement (meters), demeaned, tapered (5% or 5-second taper, whichever is shorter) and bandpass filtered into six frequency bands commonly used for discrimination (0.5–1.0 Hz, 1.0 –2.0 Hz, 2.0–4.0 Hz, 4.0–6.0 Hz, 6.0–8.0 Hz, and 8.0–10.0 Hz). Root mean square and peak-to-peak amplitude measurements were made in velocity windows defined using the phase pick time as well as fast and slow group velocities for each phase.

We calculated amplitude ratios at both ZAL and KURK for various different discriminants (high frequency P to high frequency S and high frequency P to low frequency S). Figure 9 shows the result for two of these discriminants at ZAL and KURK. The two distinct mining trends, which are evident in Figure 7, can be seen prominently on each figure. The ratios for the mining explosions vary from between –2 to 2 for all discriminants; this trend overlaps with the earthquake populations. Although there are a few events that separate from the earthquakes, the majority of events do not discriminate well. At KURK, there seem to be more events that plot outside the earthquake trend, although with the limited number of earthquakes, it is difficult to assess whether the performance of the discriminant is truly better than the ZAL case.

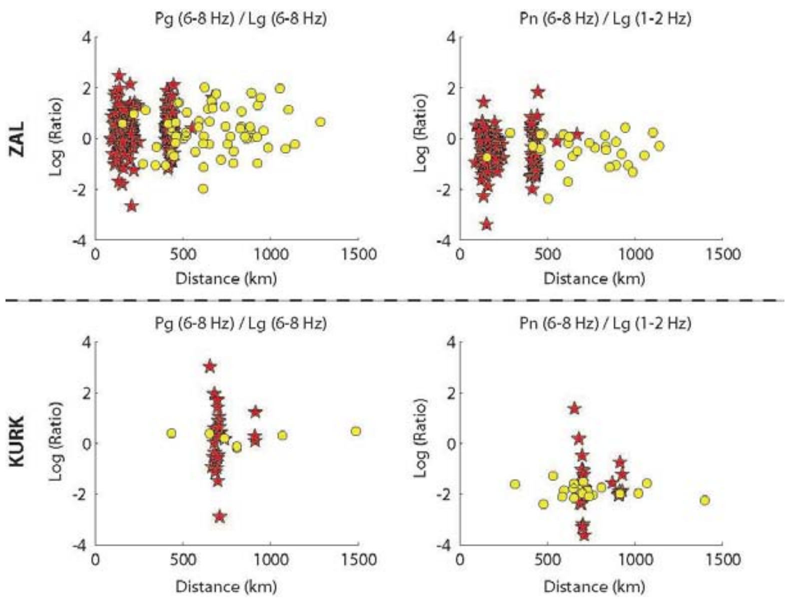

Figure 9. Uncorrected amplitude ratios measured at ZAL (top) and KURK (bottom) for probable mining explosions (red stars) and probable earthquakes (yellow circles). Data have been plotted as a function of distance for two different discriminants. Only data points with a SNR ratio of 2 have been plotted.

Time-frequency discriminant

We have applied the time-frequency discriminant to this region using data at both ZAL and KURK. The input parameters used in the method were trained to the dataset at each station using 1350 different input parameter combinations (see Arrowsmith et al., 2006c, for more details). The results indicate that the discriminant is successful for separating certain mining explosions from the general earthquake population at ZAL (Figure 10). However, the majority of mining explosions do not separate from the earthquake population at ZAL, and the discriminant is not successful at KURK. However, we note that the time-frequency discriminant only worked in the PRB for the largest event class, the cast blasts (Arrowsmith et al., 2006a). Without detailed ground truth on blast size, type and details of the timing sequence, it is difficult to fully assess the effectiveness of this discriminant in this region.

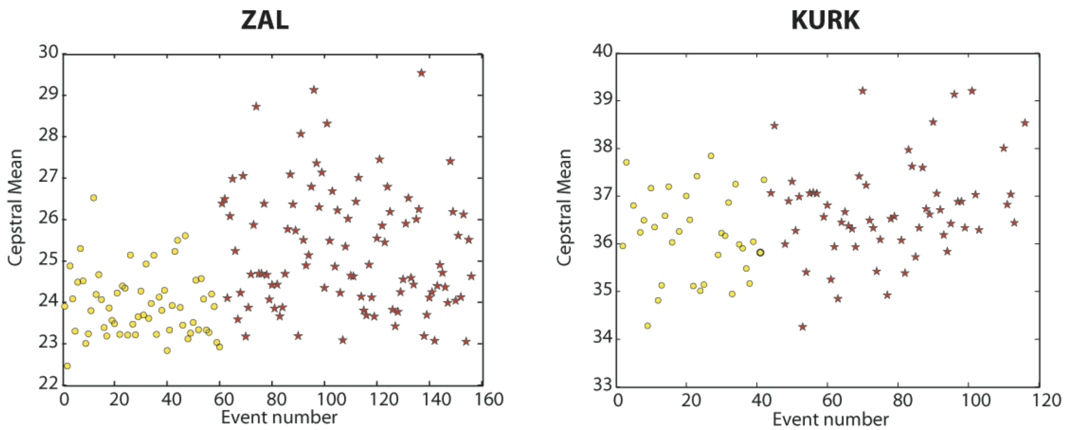

Figure 10. Time-frequency discriminant (cepstral mean) for ZAL (left) and KURK (right). Earthquakes are plotted as yellow circles and probable mining explosions as red stars.

CONCLUSIONS AND RECOMMENDATIONS

One of the main goals of this paper is to assess the effectiveness of existing mining explosion discrimination algorithms in the PRB and the AS region of Russia. Furthermore, we are interested in the comparison between the results obtained in these two regions, using a similar set of techniques. This comparison relates to the general problem of discriminant portability, whereby some discriminants are effective in certain regions but not in other regions.

The findings presented in the AS region are similar to those obtained in the PRB. Firstly, we observe that the amplitude ratio discriminants are not successful in separating mining explosion waveforms from those generated by earthquakes. These findings are also consistent with work by Jenkins and Sereno (2001) and Koch and Fah (2002), who found that the amplitude ratio discriminant was either ineffective, or ineffective for certain types of shots and/or certain stations. However, despite these findings, there is evidence that the amplitude ratio discriminant may be applicable to mining explosions in some regions (e.g., Kim et al., 1994). However, it is clear that the amplitude ratio discriminant is not as useful as it is for separating nuclear explosions from the earthquake population. In the PRB study, spectral ratios for the earthquakes showed a regional pattern with those earthquakes propagating along the same path as the observed explosions indicating some separation from the explosion data set.

We've concluded a preliminary study of infrasound generated by mine blasts in the PRB and found that given favorable winds and low station noise, an infrasound signal is often detected from large mining events, even though our monitoring station—PDIAR—was not optimally located for such a study. Given the limitations posed by the event-station geometry in our small study, we cannot draw firm conclusions regarding the utility of infrasound for ruling out a surface mine blast if a signal has not been detected under favorable conditions. Such a conclusion, perhaps employing more data collected in other areas and further research into wave propagation through our unsteady atmosphere, is needed.

Secondly, we observe that the time-frequency discriminant successfully separates some of the mining explosions from the earthquake population in both the AS and the PRB. In the PRB, we were able to show that the time-frequency discriminant separated 97.4% of a certain type of mining explosions (cast blasts) from the earthquake population (Arrowsmith et al., 2007). The cast blasts are much longer in time duration than the other mining explosions that might contribute to the success of time-frequency discriminant. However, in the AS we do not have detailed ground-truth information on the types of mining explosion. It is possible that the mining explosions that separate from the earthquake population in this region correspond to a particular blast type, but we do not have sufficient ground-truth information to check this.

During the course of this study we have encountered difficulties in obtaining detailed ground-truth information on mining explosions (as described above). This problem is common in certain countries and highlights the need to rely on secondary ground-truth information (e.g., time-of-day information and satellite imagery [MacCarthy et al., 2007]). However, for the purposes of fully assessing mining explosion discriminants, we have found that it is

necessary to obtain at least some minimal information directly from the mining operators, such as shot type and origin time. For more detailed studies, further information on shot properties, such as shot grid patterns, inter-shot and inter-row delay times, and yields are also useful. Despite the limitations of the ground truth acquired in the Russian component of the study, we have been able to provide some confidence in the bulletins through a detailed time-of-day analysis, and have been able to provide a preliminary assessment of discriminants that largely matches the results obtained in the PRB (Arrowsmith et al., 2006a).

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